Study of whistler-mode waves observed near the Moon in the solar wind

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博士論文

Study of whistler-mode waves observed near the Moon in the solar wind

（月周辺の太陽風中で観測される
ホイッスラーモード波動に関する研究）

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Abstract

The Moon is exposed to the solar wind outside the terrestrial magnetosphere and has an intrinsic plasma environment. In particular, remnant magnetic anomalies in the lunar crusts are suggested to form local mini-magnetospheres or mini-bow shocks in the spatial scale of the order of the gyroradius of solar wind protons, corresponding to a few hundred km. We study wave activities in the magnetic field near the Moon in the frequency range of several Hz in order to understand the plasma environment near the Moon and processes of the solar wind interaction. By analyzing dataset obtained by Kaguya which orbited around the Moon, we reveal the wave properties and suggest relevant processes of the wave generation mechanism.

Four types of characteristic waves are clarified: (1) narrowband wave (NR), which is mostly left-hand polarized in the spacecraft frame and appears in the frequency range at a few Hz, (2) broadband wave (BR), which has no preferred polarization and appears in the spectra up to about 10 Hz, (3) right-hand polarized broadband wave (BR-R), which is relatively weak and appears in the frequency range of several Hz, and (4) narrowband wave with its harmonics (HR). We construct criteria to select the waves and perform statistical analyses. NR shows the same properties with so-called “1 Hz waves” or “upstream whistlers” which have been observed in the upstream regions of various solar system bodies. BR is observed just above the magnetic anomalies in the solar wind and is associated with ions reflected by the anomalies. Since the other types of waves are observed near the region where BR is observed and all types of waves are identified as whistler-mode waves, NR, BR-R and HR are suggested to be a part of BR satisfying the conditions, which we clarified in the present study, during the propagation away from its source region.

The difference of the group velocity of the waves between the plasma frame and the spacecraft frame results in the difference of the wave frequency width and the spectral density in the frames. When the group velocity in the spacecraft frame approaches to zero, whistler-mode waves show an apparent peak of the spectral density at a few Hz in the spacecraft frame. We propose this condition as “group-standing” condition, which is consistent with the observed properties of NR. The essential conditions to observe BR are connection to the lunar surface through the magnetic field and ions considerably reflected from the Moon. We suggest that the relative velocity of the ions to the electrons

across the magnetic field would excite dominantly the whistler-mode waves in the frequency around the lower hybrid frequency in a regime of the modified two stream instability. Since the wave vector of BR-R has a large angle against with respect to the sunward direction, BR-R is not Doppler shifted and its frequency range corresponds to that of NR in the plasma rest frame, which is close to the local lower hybrid frequency. Fundamental waves of HR have the same properties with NR, but the propagation angle of HR is relatively larger than that of NR. This indicates that NR with a large longitudinal component becomes HR through the nonlinear steepening due to the difference of the phase velocity in the wave phase.

Based on the group-standing theory and the properties revealed by the observation, we have clarified the relation among the four types of waves around the Moon. We conclude that whistler-mode waves near the lower hybrid frequency generated by reflected ions are observed as (1) NR in the spacecraft frame when the group velocity vector points to the sunward and is cancelled by the solar wind velocity, as (2) BR in the interaction region, as (3) BR-R when the wave vector points perpendicular to the sunward, and as (4) HR when large amplitude waves satisfy the same condition with NR and the wave vector points perpendicular to the magnetic field.

In addition, we compare with similar waves observed in the upstream regions of other solar system bodies to verify the general processes of the waves. For the verification of the proposed group-standing theory, we analyze dataset obtained by Geotail in the upstream of the Earth's bow shock. We find that waves similar to NR and BR-R are observed by Geotail, but HR is not observed. Based on the properties of the waves, we conclude that NR is actually group-standing and that BR-R is not group-standing. We suggest that the group-standing effects can make it possible to observe NR far upstream from the bow shock. Although the waves in the upstream of the bow shock have almost the same properties as the waves observed near the Moon, they have small propagation angles, which would prevent the steepening of the waves to be observed as HR. We have compared the waves near the Moon with those in the upstream of the bow shock and reveal that the propagation angle, the wave intensity, and the frequency range in the plasma rest frame are different each other, possibly caused by different generation processes.

We have quantitatively clarified how the observed spectra of the waves are modified from their spectra in the plasma rest frame due to the relative velocity between the plasma rest frame and the spacecraft frame. The modification of the spectra becomes significant when the group velocity of the waves is comparable to the relative velocity, because of the group-standing effects. We reveal that the observed spectra are not necessarily identical with those determined by the wave generation process in the plasma rest frame, as shown by the relation between NR and BR-R. We propose that the thorough understanding of the observational properties of the waves is essential to elucidate the generation mechanism of the plasma waves, which serve important clues in drawing the comprehensive picture of the solar wind interaction with solar system bodies.